# Gliese 569B: A young multiple brown dwarf system?

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## ABSTRACT

The nearby late M star Gliese 569B was recently found by adaptive optics imaging to be a double with separation $\sim 1$ AU. To explore the orbital motion and masses, we have undertaken a high resolution ($\sim 0\farcs05$) astrometric study. Images were obtained over 1.5 years with bispectrum speckle interferometry at the 6.5m MMT and 6m SAO telescopes. Our data show motion corresponding to more than half the orbital period, and constrain the total mass to be $> 0.115\,M_{\odot}$, with a most probable value of $0.145\,M_{\odot}$. Higher masses cannot be excluded without more extended observations, but from statistical analysis we find an 80% probability that the total mass is less than $0.21\,M_{\odot}$.

An infrared spectrum of the blended B double obtained with the MMT has been modeled as a blend of two different spectral types, chosen to be consistent with the measured $J$ and $K$ band brightness difference of a factor $\sim 2$. The blended fit is not nearly as good as that to a pure M8.5+ template. Therefore we hypothesize that the brighter component likely has two unresolved components with near equal masses, each the same as the fainter component.

If Gl 569B is a triple our dynamical limits suggest each component has a mass of $50^{+23}_{-4}\,M_{jup}$. We infer an age for the system of 300 Myr, from its kinematic motion which places its as a member of the Ursa Major moving group. All the above parameters are consistent with the latest DUSTY evolutiuon models for brown dwarfs.

*Subject headings:* binaries: general — stars: evolution — stars: formation — stars: individual (Gl 569) — stars: low-mass, brown dwarfs

## 1. Introduction

Gliese 569 has been known for some time as a binary star 9.8 pc distant, with two M stars at a projected separation of 50 AU. The low mass secondary (subsequently designated 569B) was found through infrared imaging (Forrest, Skrutskie & Shure 1988). Visible imaging and low resolution spectroscopy of this component suggested it to be a M8.5 dwarf (Henry & Kirkpatrick 1990) although rather luminous for its age when compared to other cool field dwarfs (Forrest, Skrutskie & Shure 1988). In 1999, Martín et al. (2000) (hereafter M00) imaged the fainter B component with the Keck II adaptive optics system and found it to be a binary with projected separation of 1 AU and $\sim 0.7$ magnitude brightness difference. A determination of the mass of the system from orbital motion is thus possible and of particular interest, since it is thought (from stellar activity indicators) to be young, between 0.1 and 1.0 Gyr (M00). At this age the components of Gl 569B are good brown dwarf candidates. There has been little chance to test brown dwarf models against objects of known mass from direct dynamic measurement, although a lower mass limit was obtained by Basri & Martín (1999) for the spectroscopic brown dwarf binary PPl 15.

## 2. Astrometric imaging by bispectrum speckle interferometry

We imaged the Gl 569 system with the Bonn IR speckle camera on 2000 July 4 at the new 6.5m Multi-Mirror Telescope (MMT), 10 months after the original discovery image (M00), and again on 2001 March 9 and 10 at the Special Astrophysical Observatory (SAO) 6m telescope in Russia. In both cases reimaging optics were used so as to properly sample diffraction limited speckles. At the MMT the images were recorded in the $H$ and $K$-band with pixel sizes of $18.70 \pm 0.19\,mas$ and $24.68 \pm 0.25\,mas$, and at the 6m telescope images were recorded in both the J and H bands, with $13.33 \pm 0.13\,mas$ and $20.11 \pm 0.20\,mas$ respectively. The seeing was typically $1\farcs0$—$1\farcs5$ over all nights.

EDITOR: PLACE FIGURE 1 HERE.

Diffraction-limited images of the triple system were reconstructed using the bispectrum speckle interferometry method described in Weigelt (1977), Lohmann, Weigelt & Wirnitzer (1983) and Hofmann and Weigelt (1986). The bispectrum of each frame consisted of 113 million elements and the object power spectrum was determined with the speckle interferometry method, (Labeyrie 1970). The unresolved bright point source Gl 569A of the wide ($5\farcs0$) binary served as a reference star for the determination of the speckle transfer function and the resulting images are diffraction-limited images (Figure 1). The pixel scale was derived from measurements of several wide calibration binaries with well-known separation and position angle (with separation error $\leq 1\%$ and position angle error $\leq 1^{\circ}$).

The position angles, radial separation and associated measurement errors are given in Table 1. Also listed for completeness is the published discovery data from the Keck II telescope (M00).

EDITOR: PLACE TABLE 1 HERE.

## 3. Orbital solution for Ba/Bb

Solutions for the orbital elements of the close binary Ba/Bb were found from the three epochs of observation, using classical astrometric techniques (Aitken 1964). Although the data points are well placed to cover most of the orbit, a unique solution is not possible without more extended observations. Nevertheless, we are able to place analytically a strong lower limit to the combined mass. Orbits which exactly fit the data are not possible for a combined mass of less than $0.136\,M_{\odot}$, and for a wide range of assumed eccentricity

(0.3 to 0.5) the mass lies between 0.136 and 0.150 solar masses, with the corresponding periods from $2.3 - 3.5$ yr and the semi-major axes lying between $0.93 - 1.25$ AU.

In order to explore the effect of measurement errors and the possibility that we happened to catch a higher mass system with wider spacing at higher inclination, we constructed a Monte Carlo model. Many trial binaries were constructed with uniform distribution in total mass, ellipticity and period. The epoch of periastron ($t$) was chosen randomly within the range $0 < t < P$ with $P$ up to 10 yr and viewing directions were modeled as from points uniformly distributed over a sphere. The ephemeris was calculated and the calculated positions for the three observed epochs compared with the observations. If the orbit matched the data to within $2\sigma$ of each of the three observed data points, the orbital elements of that orbit were noted, along with the combined mass of the system.

The mass distribution found in this way is non-gaussian (see inset Figure 1), with 80% in the range $0.115 - 0.216\,M_{\odot}$ and the remaining highest 20% forming a high mass tail. We conclude that the combined mass for Gl 569B is $0.144^{+0.059}_{-0.010}\,M_{\odot}$ for 20%—80% limits, with a hard lower mass limit of $0.115\,M_{\odot}$, consistent with the analytically derived orbital fits. Our present astrometry cannot yield the division of mass between the individual components.

## 4. Spectral types and temperatures of Gl 569Ba and Gl 569Bb

We obtained $J, H, K$ spectra of Gl 569A and the B component blend on 4 March 2001 1230 UT at the 6.5m MMT Observatory with the FSPEC IR spectrograph (Williams, Thompson & Rieke 1993). FSPEC is a cryogenic long slit near-IR ($1 - 2.5\mu$m) spectrograph which we used at the low ($R \sim 700$) resolution mode. The spectra were taken and reduced with standard IR beam-switching techniques. Terrestrial lines were removed by observing a F9V star just before and after the Gl 569 science exposure, and at a nearly identical

airmass. The F9 and the Gl 569B spectra were extracted with standard IRAF routines and wavelength calibrated with the OH night sky emission lines. No contamination from Gl 569A was observed.

We have compared the observed K-band spectrum of Gl 569B (containing both Ba and Bb) to late M star dwarf standards taken during the same run and have modeled it as a sum of two spectra corresponding to the observed difference in $K$ magnitude of 0.7. It appears that a minimization of the residuals occurs when "deblending" Gl 569Ba by 65.5% M8.0 and 34.5% M9.5. In Figure 2 we show the effective spectrum of "Gl 569Bb" assuming that 65% of Gl 569B's light is from Gl 569Ba being a M8.0 star. This "Gl 569Bb" spectrum appears in the K band to be closest to a M9.5. We also show a fit of "Gl 569Bb" to a M9.5 template and show 9.4% rms error in the fit. Even though this was our best blended fit, there are large residuals and poor fit to the CO features. No mix of a cooler and hotter star weighted by $\Delta K = 0.7\,\mathrm{mag}$ works well.

EDITOR: PLACE FIGURE 2 HERE.

EDITOR: PLACE TABLE 2 HERE.

However, much to our suprise, we found that the IR ($1 - 2.5\mu$m) spectrum from Gl 569B was very well fit by a pure M9 template spectrum. The rms residual from just fitting Gl 569B to a M9 spectrum yielded a fit of only 1.4% rms error and excellent fits to the CO features.

We examined our J spectra and measured the equivalent widths for both the K I doublets and the steam feature at $1.34\mu$m (see Table 2). Based on these measurements and the best spectral type indices of Reid et al. (2001) we find that Gl 569B is easily and

consistently classed as a M8.5-M9 (M8.5+) with a $T_{eff}$ of $2150 \pm 75$ K from the template scale of Leggett et al. (2001). These temperature errors do not take into account the $\sim 300$K systematic offsets between different models, $\pm 75$ K is simply a relative temperature error. This choice of temperature scale is optimal since the same Ames dusty atmospheric features and opacities were used in the full DUSTY tracks (Chabrier et al. 2000, 2001) and so any systematic offsets in the stellar temperatures and the DUSTY model temperatures are minimized with this choice of temperature scale. Moreover, as discussed in Leggett et al. (2001) this temperature scale has a relative accuracy ($\pm 75$ K) for the M7-L3 SpT considered here where dust opacity plays a large role.

Again, when we attempt a separation as two components of different brightness, the J band residual spectrum "Gl 569Bb" extracted from the Gl 569B spectrum appears poorly fit by any template. However, we can classify this "Gl 569Bb" somewhere in the M9.5-L3 range with a $T_{eff}$ of $1985 \pm 120$ K. The large error in this $T_{eff}$ again suggests that this extracted "Gl 569Bb" spectrum is not physical and so does not match any spectral type well. Therefore it appears both Bb and Ba are best fit by an M8.5+ spectrum for both the bright and faint components.

## 5. Age of the Gliese 569 System

Since age is critical to expected luminosity for such late stars, we have examined the kinematic evidence, with a view to obtaining a more accurate estimate. We calculate the heliocentric UVW velocity for Gl 569A using the proper motion and parallax from Hipparcos (HIP 72444), the radial velocity of Marcy, Lindsay & Wilson (1987) ($v_r$ = –7.17 $\pm$ 0.28 km s$^{-1}$) and employ a galactic motion vector algorithm (J. Skuljan 2000, private communication). We find a UVW vector of (+7.8, +3.2, –13.3) km s$^{-1}$, with uncertainties of (0.2, 0.1, 0.3) km s$^{-1}$. Comparing this vector with Soderblom (1990) scatter plots of

the UVW motions of nearby active dwarfs, we noticed that it is very close to that of the Ursa Major (UMa) moving group (+12.6, +2.1, –8.0; Soderblom et al. (1993)), with Gl 569 within 7.2 km s$^{-1}$ of Soderblom's space motion for the UMa group.

The age of the UMa nucleus is $\simeq$0.3 Gyr (Soderblom et al. 1993), however there is a somewhat larger spread in age when one examines the early-type stellar content of the UMa moving group on larger scales (Asiain et al. 1999; Chen et al. 1997). From the correlation between the young age inferred from stellar activity indicators, and the kinematic similarity between Gl 569 and the UMa moving group, we suggest that it is a member of the moving group with an age of $0.3 \pm 0.1$ Gyr. We also note that the slightly subsolar metallicity of Gl 569A ([M/H] = –0.15; Zboril & Byrne (1998)) is similar to the value for the Ursa Major nucleus stars ([Fe/H] = $-0.08 \pm 0.09$; Soderblom et al. (1993)).

## 6. Discussion

We have seen in Section 4 that the blended spectrum of Ba/Bb matches that of a single M8.5+ star with much smaller residuals than a blend of an M8.0 and M9.5. We therefore postulate that all the light from Gl 569B (containing both Ba and Bb) is from an M8.5+ spectral type. Moreover, we have independently found that the $\Delta J - \Delta K$ differential colors of the Ba and Bb component are $-0.10 \pm 0.14$ mag, in close agreement with the value of $0.0 \pm 0.14$ observed by M00. Therefore, we see no evidence of Bb being any redder than Ba while appearing only half as bright! As Table 2 points out, the expected $\Delta J - \Delta K$ color for a binary composed of a M8.0 and a M9.5 is $\Delta J - \Delta K = (J-K)_{M9.5} - (J-K)_{M8.0} = 0.30$ mag. Since 0.3 mag is inconsistent (at $3\sigma$) with the $\Delta J - \Delta K = -0.10 \pm 0.14$ observed it is difficult to understand how Gl 569B can be composed of 2 stars of different spectral types.

It appears that both Gl 569Ba and Gl 569Bb have the same temperature. However,

since Gl 569Ba is $1.9 \pm 0.2$ times as bright as Gl 569Bb, the most logical explanation for this overluminosity is that Gl 569Ba is *itself* a binary star (as first suggested by M00). Moreover, the lack of any blended spectral features cooler than M9 in the Gl 569B spectra argue that the Gl 569Ba binary is likely composed of 2 stars both close to M8.5-M9.0 in spectral type. Hence, we conclude that Gl 569Ba is most likely a close ($\leq$ 0.1 AU) binary with nearly equal magnitude components. Therefore the Gl 569B system becomes a hierarchical triple with Gl 569Bb orbiting around a binary Gl 569Baa and Gl 569Bab. All 3 of these stars should have nearly identical M8.5+ spectral types and therefore very similar masses.

We now examine the models models of Chabrier et al. (2000, 2001) and see how treating Ba/Bb as a double system compares to a triple system model. In order to do this, we adopt the photometry of the combined Gl 569B system from Forrest, Skrutskie & Shure (1988), who measured $K = 9.56 \pm 0.1$. The individual absolute magnitudes follow from our measured brightness ratios given in Table 1 and the parallax $d = 101.91 \pm 1.67\,mas$ from Hipparcos (Perryman et al. 1997). We take the values to be $M_K(Ba) = 10.02 \pm 0.12$ mag and $M_K(Bb) = 10.72 \pm 0.12$ mag.

EDITOR: PLACE FIGURE 3 HERE.

Figure 3 shows Ba/Bb considered both as a double system (hollow circled points) and as a triple system with Ba composed of two equal mass objects (filled circles). For the binary case, it is clear that although Bb gives marginal agreement to its uncertain spectral type of M9-L3, it is Ba that stands out as an object much more luminous than spectral fitting and typing to an M8.0 would suggest. However, considering B to be a triple system results in all three components of nearly equal mass (the two Ba components are $0.049\,M_\odot$ each and Bb is $0.057\,M_\odot$), a SpT consistent with an M8.5+, a $\Delta J - \Delta K \sim 0$ (as observed), and a model age in good agreement with a kinematically derived age of $0.3 \pm 0.1\,$Gyr.

The astrometric and spectroscopic results presented here suggest that Gl 569B is a young heirarchical triple brown dwarf system with three nearly equal components of $\sim 50^{+23}_{-4}\,M_{jup}$ each, and a dynamically constrained lower mass sum of $M = 0.115\,M_{\odot}$. The work reported here must therefore be regarded as simply a step to understanding what promises to be a key brown dwarf system. Continued high accuracy astrometric measurements, as represented by our third epoch measure ($\pm 1\,mas$), should yield an accurate and unambiguous total mass for the system. Furthermore, by careful calibration of plate scale, accurate measurement of the two stars individual motions should be possible, so individual masses can be derived with no recourse to theoretical models, and high resolution spectroscopy is required to see if Ba is indeed a spectroscopic binary.

Some of the observations reported here were obtained at the MMT Observatory, a joint facility of the University of Arizona and the Smithsonian Institution. We thank Isabelle Baraffe for supplying us with theoretical models computed by France Allard, Isabelle Baraffe, Gilles Chabrier and Peter Hauschildt, and Mike Meyer for helpful discussions. MAK acknowledges support by the AFOSR under F49620-00-1-0294.

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Table 1. Measured properties of the Gliese 569 B System

| Epoch | Telescope | PA (deg) | Separation (mas) | $\Delta J$ | $\Delta H$ | $\Delta K$ | Resolution (mas) |
|---|---|---|---|---|---|---|---|
| 1999.654 | Keck 10m[a] | 48±2 | 101.0±2.0 | 0.5±0.2 | 0.5±0.1 | 0.5±0.1 | 50 |
| 2000.501 | MMT 6.5m | 148±3 | 78.0±3.0 | ··· | 0.7±0.1 | 0.7±0.1 | 53 |
| 2001.186 | SAO 6.0m | 321±1 | 89.6±1.0 | ··· | 0.9±0.1 | ··· | 57 |
| 2001.189 | SAO 6.0m | 320±1 | 89.9±1.0 | 0.6±0.1 | ··· | ··· | 53 |

[a]Results from Martín et al. (2000) included for comparison

Table 2. Measured equivalent widths for Gl 569B

| Star | K I 11690Å | K I 11770Å | K I 12440Å | K I 12530Å | $H_2O$ 1.34/1.29$\mu$m | K-Band SpT $2.05-2.40\mu$m | Adopted SpT | Adopted $T_{eff}$[a] (K) | Typical $(J-K)$[b] for Adopted SpT |
|---|---|---|---|---|---|---|---|---|---|
| GL569B | 5.48 (M8) | 7.52 (M9) | 9.93 (M9) | 9.44 (M8.5) | 0.76 (M9) | M8.5+ | M8.5+ | $2150 \pm 75$ | 1.20 |
| "GL569Bb" | 10.13 (L3) | 10.42 (L3) | 13.00 (L3) | 12.80 (L3) | 0.68 (L1) | M9.5 | M9.5-L3 | $1985 \pm 120$ | 1.45 |
| M8 template[c] | 5.29 (M8) | 7.12 (M8.5) | 8.72 (M8.0) | 7.40 (M7.5) | 0.81 (M7) | M8.0 | M8.0 | $2225 \pm 75$ | 1.05 |

[a]temperature scale from Leggett et al. (2001)

[b]typical colors from Reid et al. (2001)

[c]Our M8 template star was 2MASSW J1444171+300214

Note. — all spectral types fit to the SpT indices of Reid et al. (2001)

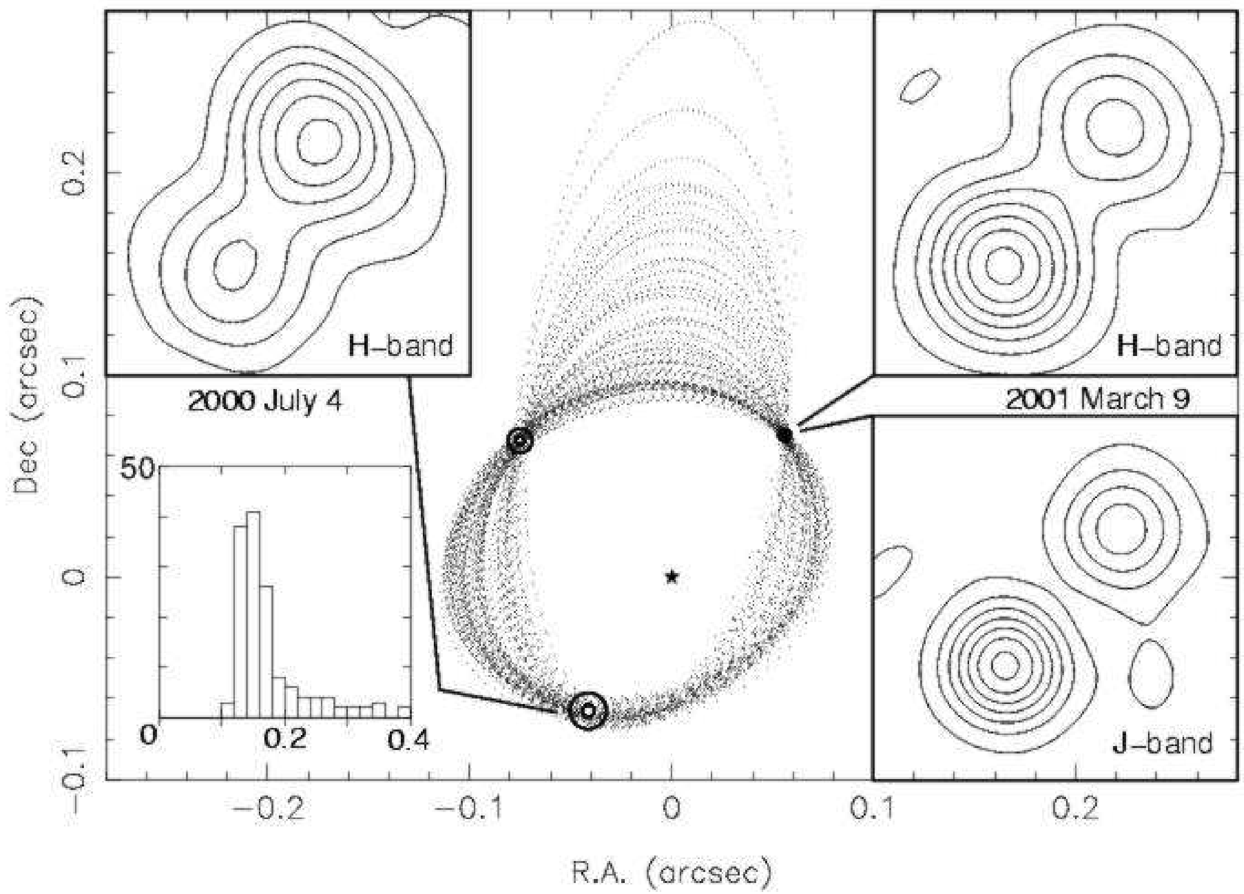


Fig. 1.— The orbital solutions found which all pass within $2\sigma$ of each observed epoch. The solid inner circles are $1\sigma$ error bars and the outer circles are $3\sigma$. Ba is at the center of the frame with Bb orbiting it. The MMT and SAO bispectrum speckle images (inset) are shown with the highest contours at 95% of the peak value and decreasing in steps of 10%. The orbital solutions and the reconstructed images have the same scale. North is up and East to the left for all images. The histogram in the lower left corner shows the distribution of mass (in units of Solar mass) for all accepted orbital solutions.

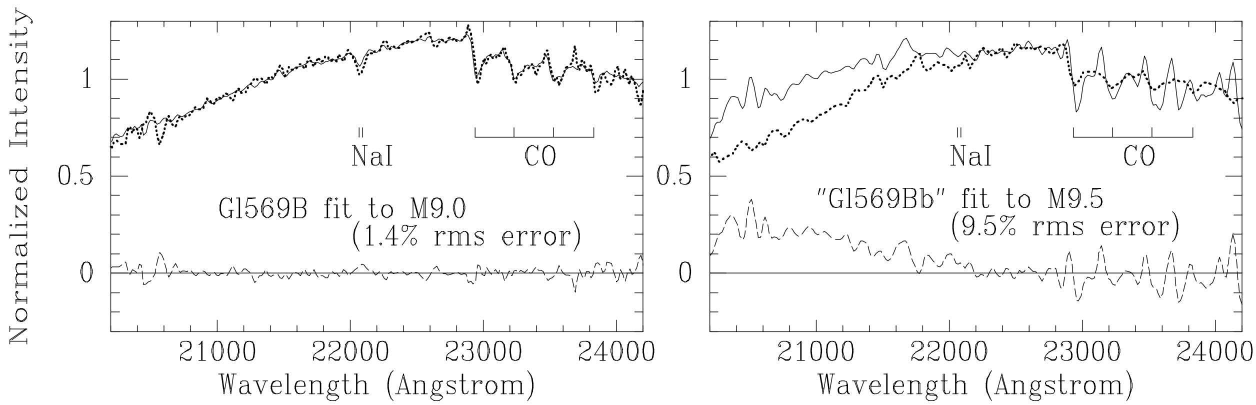


Fig. 2.— The left-hand plot shows a fit of the observed GL569B $K$ band spectrum (solid line) with our M9.0V template star (BRI1222-1221; dotted line). The excellent match (residuals are plotted as the dashed line) shows the blended light from Gl 569Ba and Bb appears consistent with just a M9.0 spectrum. The plot on the right is similiar except that the residual "Gl 569Bb" de-blended spectrum is fit to a M9.5. Even though this "Gl 569Bb" was our best deblended spectrum and M9.5 was the closest spectral match in the $K$ band, it is shown to have a poor fit with a large residual error. Hence, our deblending efforts of Gl 569B's spectra into a hotter star and a cooler are much less successful than just a pure M8.5-M9 spectrum.

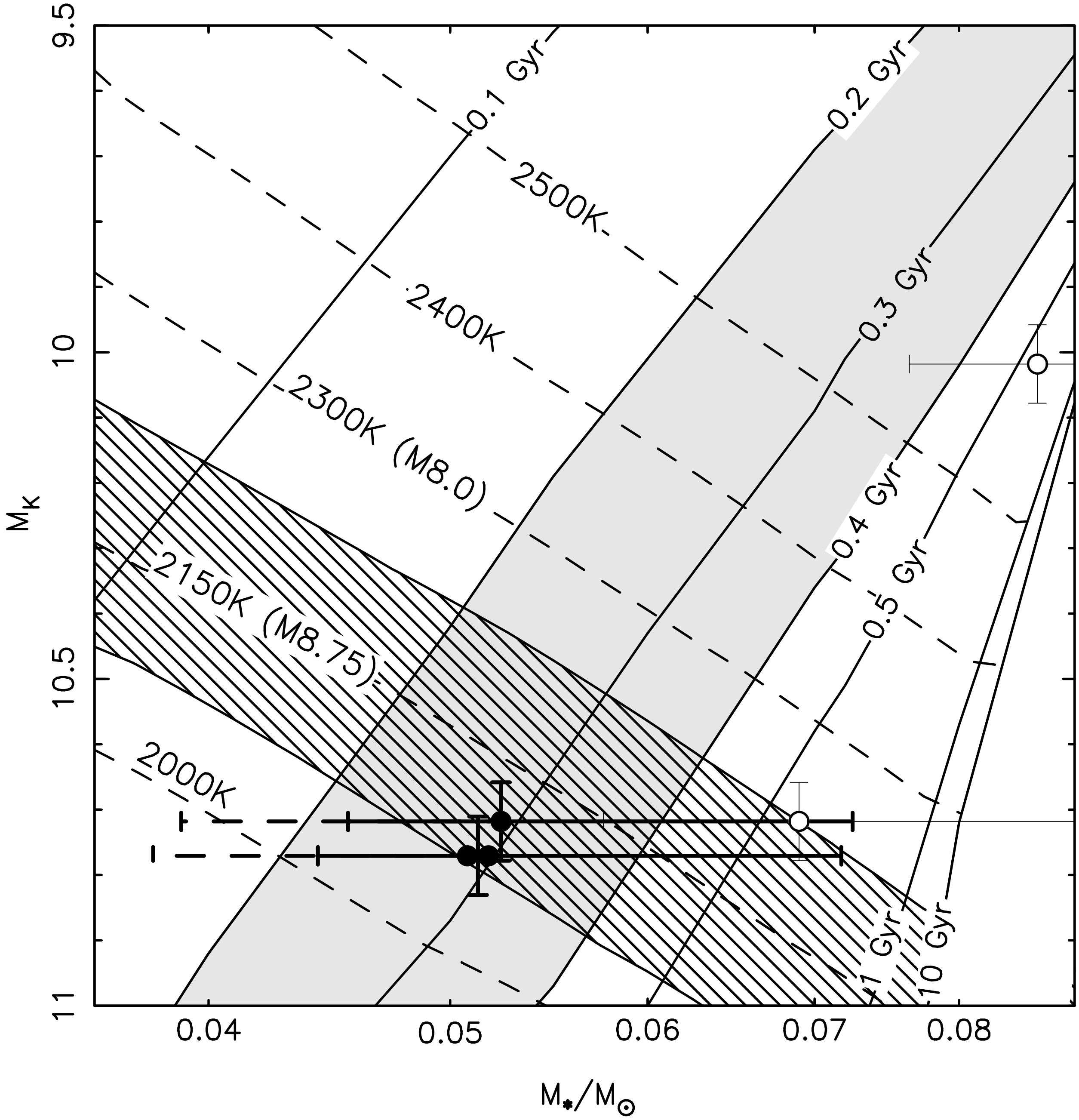


Fig. 3.— Mass-$M_K$ diagram for Gl569Ba/Bb for the cases where Ba is either a single or a double star. The shaded isochrones represent the estimated age range for the UMa stream. The hollow circles represent the positions of Ba and Bb if Ba is a single star. The solid circles represent Ba and Bb if Ba is treated as an equal mass binary. In both cases, mass error bars are for $1\sigma$ confidence limits and the hard lower mass limit is represented as a dotted extension to the mass error bars. The isotherms have SpT associated with them according to models from Chabrier et al. (2000); Leggett et al. (2001).